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Reservoir Potential of Datta Formation, Hazara Basin, Pakistan

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ABSTRACT

The Datta Formation of Toarcian age is predominantly a transgressive shoreface facies in the Hazara Basin. The four standardized lithofacies include Carbonate Facies (D1), Argillaceous Facies (D2), Arenaceous Facies (D3) and Ferrogenous Hardground Facies (D4) which have been subdivided into various microfacies.

The Datta Formation was deposited under repeated fluctuating sea level conditions. This predominantly clastic shoreface facies is, therefore, intercalated with the lagoonal shale beds, hardgrounds, carbonate shoals, lagoonal pelletoidal limestone horizons, glauconitic subtidal sandstone, minor shallow tidal channels and barriers which shows cyclic deposition.

The porosity of the Datta Formation in Hazara Basin generally varies from 1 to 7%. However in some upper shoreface horizons this formation has high porosity (upto 20%) and may serve as a hydrocarbon reservoir in northern Potwar.

The study of heavy mineral suits, their quantities, and shapes suggests a recycled origin for the clastic part of the Datta Formation.

INTRODUCTION

The Datta Formation (Danilchick, 1961; Shah, 1977) of Early Jurassic age is persistant and important lithostratigraphic unit exposed in Hazara Basin (Chaudhry and Ahsan, 1999; Chaudhry et al., 1998), Attock and Upper Indus Basin of Pakistan (Chaudhry et al., 1995; 1997). Gee (1945) and earlier workers named it as variegated stage. The name Datta Formation has also been applied to the lower parts of Samana beds of Davies (1930) in parts of Kohat, Kalachitta and Hazara, Red beds and part of Kioto Limestone of Middlemiss (1996) and lower part of Maira Formation of Davies and Gardezi (1965).

The type section is located in Datta Nala (Lat.: 30° 00' N; Long: 71° 19' E) in the Surghar Range. The thickness at type locality is 212 m. The maximum thickness of Datta Formation is 400 m in Shaikh Budin Hill in Surghar Range.

In the Hazara Basin it overlies unconformably Hazira Formation of Cambrian age or Hazara Formation of Late Pre-Cambrian age (Table 1). In Kohat and upper Indus Basin it overlies Kingriali Formation. It is overlain by Samana Suk Formation in Hazara Basin (Chaudhry and Ahsan, 1998) and in Attock (Baloch, 1986) it is overlain by Shinawari Formation.

Contrary to description of Shah (1977) Shinawari Formation can hardly be identified as a distinct lithostratigraphic unit in the Hazara Basin.

The age of Datta Formation has generally been considered as Pre Toarcian (Shah, 1977).

Table 1. Stratigraphic table of studied area.

Age	Formation	Lithology
Early Eocene	Margala Hill Limestone	Nodular foraminiferal limestone
Late Paleocene	Patala	Greenish grey / khaki shales with limestone
Middle Paleocene	Lockhart Limestone	Nodular foraminiferal limestone
Early Paleocene	Hangu	Sandstone, claystone, laterite.
------------ Disconformity ------------		
Late Cretaceous	Kawagarh	Fine grained, light grey limestone
Early Cretaceous	Lumshiwal	Grey to brownish coarse sandstone
Late Jurassic to Early Cretaceous	Chichali	Dark grey shales with medium grained sandstone beds
------------- Disconformity ---------------		
Middle Jurassic	Samana Suk	Limestone with dolomitic patches
Early Jurassic	Datta	Calcareous siltstone, sandstone, limestone, marl and shales
---------------- Unconformity ------------		
Late Precambrian	Hazara	Slates, sandstone and quartzites

LITHOLOGY OF DATTA FORMATION IN HAZARA BASIN, ATTOCK AND UPPER INDUS BASIN

Six sections of Datta Formation were measured (Tables 2 to 7) in detail in the Hazara Basin (Figure 1), from Thai, Kala Pani (Chaudhry et al., 1994) Bara Qatar (Chaudhary et al., 1994), Batangi, Chanath and Jaster Gali (Chuhan et al., 1992).

At Thai, the Datta Formation is poorly developed and 0.6m thick. The reasons are sedimentological rather than structural. It is composed of light greyish rusty brown to off whitish sublithic arenite and quartz arenite. It is medium bedded.

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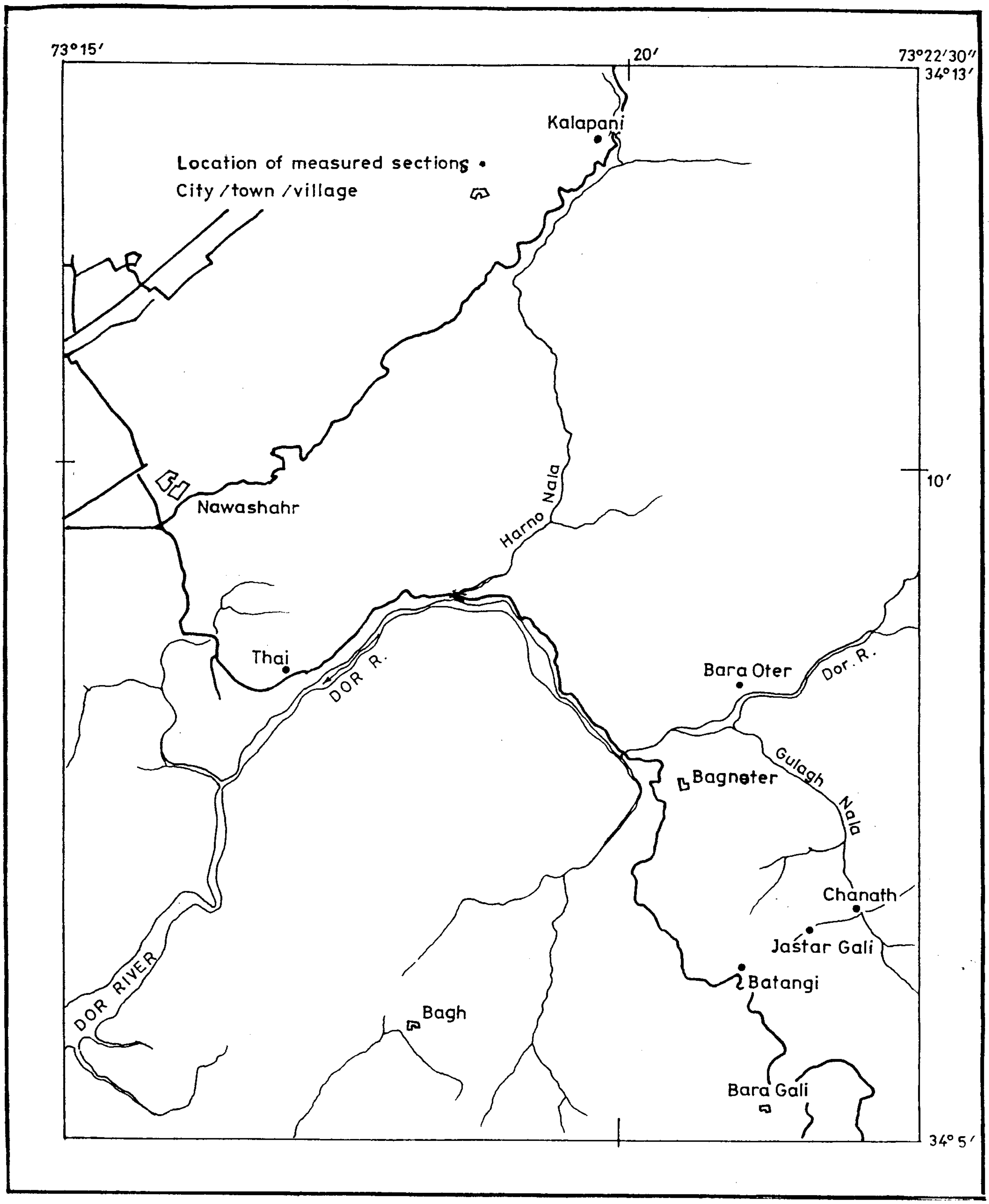

Figure 1- Location map of measured section of Datta Formation in Hazara Basin.

Table 2. Facies, microfacies and environment of deposition of Datta Formation at Thai.

Facies	Microfacies	Environment of Deposition
TIV - Sublithic Quartz Arenite	**Carbonate and Iron Oxide Cemented Quartz Arenite**: It is fine to very fine grained subangular and moderately sorted. It is light rusty brown on fresh surface and offwhitish to rusty offwhitish on weathered surface. It contains small pebbles, slate and wackes. It also contains small rock fragments of rusty gritty sandstone erroded from underlying bed of Datta Formation. Bedding is 15cm thick.	Upper Shore Face
TIII - Hard Ground	Iron Oxide Cemented Quartz Arenite: It is composed of coarse grained quartz.It is subangular to subrounded and moderately well sorted. it is red on fresh surface.	Subareal
TII - Very Fine to Fine Grained Quartz Arenite	**Carbonate Cemented Quartz Arenite**: It is very fine to fine grained, bimodal, subangular to subrounded and moderately sorted. It is light rusty brown on fresh surface and weathers to rusty brownish grey. Beds are 12 cm thick.	Middle to Upper Shore Face
TI- Sublithic Arenite and Hard Ground	**Iron Oxides Cemented Quartz Arenite:** It is composed of coarse grained quartz arenite. It contains subangular to angular clasts of shale. It is moderately well sorted. It is reddish to maroon.	Subareal

The section of the Datta Formation exposed at Kala Pani is 17.96m thick. It is composed predominantly of quartz arenites with one horizon of quartz wacke, two horizons of arenaceous limestone and a laterite band. Its fresh colour is dark grey, light grey to rusty brown which weatheres to light grey to rusty greyish brown, greyish red to dull red.

The Datta Formation at Bara Oter is 11.37m thick. It is composed mainly of quartz arenites with beds of arenaceous, dolomitized oolitic and pelletoidal limestone, hard grounds and silty mudstones. Towards the top a thin layer of grit occurs. Its weathered colour is greenish grey, light grey, rusty grey, light brown grey and rusty yellowish grey. The fresh surface is generally medium to dark grey.

The section of Datta Formation exposed at Batangi is 15.82m thick. It contians hard grounds, quartz arenites, arenaceous limestone and oolitic/pelletoidal packstone. At the base the formation is gritty. The fresh colour of the formation varies from dark grey, light grey, off whitish grey to rusty brownish grey.

The Datta Formation at Chanath is 17.65m thick. It is composed of gritty sublithic arenites, gritty arenites, arenaceous limestone, nodular limestone, oolitic and pelletoidal limestone with occasional dolomitic and shaly horizons. The standstones are cross bedded at places. Microconglomerate occurs in the basal portion. The fresh colour of the formation ranges from dark grey to light grey and palish offwhite. The weathered surface is light grey, brownish grey, palish/yellowish brown to light brown and pinkish grey. The shale is dark grey to black.

The Datta Formation at Jaster Gali is 18.40m thick. The formation is composed of quartz arenites with beds of dolomitized, oolitic and pelletoidal limestones, hard grounds with intercalations of marl and shale. Towards the bottom and top a thin layer of grit occurs. Marl is nodular, and thinly laminated. The fresh colour of the formation varies from dark grey to light grey and off white. The weathered surface is light grey and rusty brown to rusty grey.

In the Attock region (Baloch, 1986) the Datta Formation varies from 20m-30m in thickness. It is composed of variegated sandstone, shale, siltstone and mudstones with irregularly distributed calcareous, dolomitic, carbonaceous, ferruginous and fire clay horizons., Fire clay occurs in the basal portion.

FACIES OF DATTA FORMATION

The Data Formation in the Hazara Basin contains four facies which include Carbonate Facies (D1), Argillaceous Facies (D2), Arenaceous Facies (D3) and Hardground Facies (D4), and are divided into number of microfacies as follows:-

D1. Carbonate Facies
- 1a) Bioclastic mudstone-packstone
- 1b) Oolitic (bioclastic) packstone
- 1c) Pelletoidal (bioclastic) packstone
- 1d) Arenaceous mudstone
- 1e) Arenaceous dolomite
- 1f) Marl

D2. Argillaceous Facies
- 2a) Silty/Clayey Shale

D3. Arenaceous Facies
- 3a) Quartz cemented quartz arenite (fine, medium, coarse)
- 3b) Carbonate cemented quartz arenite (fine, medium, coarse)
- 3c) Quartz and carboante cemented quartz arenite (fine, medium, coarse)
- 3d) Quartz and clay cemented quartz arenite (fine, medium, coarse)
- 3e) Quartz wacke.
- 3f) Sublithic quartz arenite
- 3g) Glauconitic quartz arenite (Rare)

D4. Hardground Facies
- 4a) Haematite/ clay/ carbonate/ quartz cemented quartz arenite

Table 3. Facies, microfacies description of measured section of Datta Formation at Kala Pani from bottom to top.

Facies	Microfacies	Environment of Deposition
KVI- Fine Grained Quartz Arenite	**3. Carboante, Quartz and Clay Cemented Quartz Arenite**: Fine grained, subangular to subrounded, and moderately well sorted. Light grey to light brown on fresh surface, medium rusty brown to grey.	Lower Shore Face
	2. Carbonate, Quartz, Clay and Iron Oxides Cemented Quartz Arenite: Fine grained, subangular to subrounded and moderately sorted. Light grey to light brown on fresh surface, medium rusty brown to grey rusty brown on weathered surface.	Lower shore face
	1. Carbonate, Iron Oxides (and clay) Cemented Quartz Arenite: Fine grained, bimodal, subrounded but poorly sorted. Light grey to light brown on fresh surface and medium rusty brown to grey rusty brown on weathered surface.	Lower shore face
KV - Arenaceous Limestone	**1. Arenaceous Wackestone:** The clastic part is fine grained, subrounded, moderately sorted quartz grains in abundant sparry cemnt. Light grey to light yellowish on fresh surface, light greyish brown to light rusty yellow on weathered surface	Lagoonal
KIV- Fine Grained Quartz Cement	**3. Carbonate Cemented Quartz Arenite:** Fine grained, subrounded, moderately well sorted and fossiliferous quartz arenite. Medium grey on fresh surface and light rusty grey on weathered surface.	Lower shore face
	2. Carboante, Clay and Haematite/Limonite Cemented Quartz Arenite: Fine grained subrounded and moderately well sorted. On fresh surface medium grey white light rusty grey on weathered surface.	Lower shore face
	1. Carbonate and Clay Cemented Quartz Arenite: Fine grained, subangular to subrounded and moderately well sorted quartz grains. Medium grey on fresh surface and light rusty grey on weathered surface.	Lower shore face
KIII - Hard Ground	**2. Clay and Haematite Cemented Quartz Wacke:** Fine grained, subangular to subrounded moderately well sorted clay and haematite cemented quartz wacke. Medium grey on fresh surface and yellowish grey on weathered surface.	Lower to Middle Shore Face
	1. Hard Ground/Laterite: Limonite/Haematite with subordinate medium grained subrounded and moderately well sorted quartz grains. Fresh surface dull red to grayish red, weathering surface deep rusty brown.	Subareal residual deposit
KII - Pelletoidal Limeston	**1. Pelletoidal Packstone:** Pellets are fine to medium grained and moderately well sorted. Very dark grey on fresh surface, medium rusty brown to grey on weathered surface.	Lagoonal
KI - Very Fine to Fine Grained Quartz Arenite	**2. Carbonate and Quartz Cemented Quartz Arenite:** Fine grained subangular to subrounded, moderately well-sorted carbonate and quartz cemented quartz arenite. Medium to dark grey on fresh surface having thin carbonate layers.	Lower to Middle Shore Face
	1. Carbonate Cemented Quartz Arenite: Very fine grained, subrounded and well sorted. Medium grey on fresh surface, light rusty on weathered surface with few slate clasts.	Lower shore face

The Datta Formation is characterized by rapid lateral as well as vertical variations in the occurrence of facies and microfacies. This may be related to rapid variation in sea level and original topography of the under lying formations on which Datta Formation was deposited. Reworking, stratigraphic breaks and erosion of already deposited facies and microfacies is evident from incomplete cyclicity, sedimentological breaks and erosional surfaces. It is therefore not possible to correlate in time and space the various sections. Synchroneity of various units cannot be established since the formation is devoid of index fossils.

Facies and microfacies of Datta Formation are described in the following:

Facies and Microfacies

D1 Carbonate Facies

This facies is composed of varying percentages of allochems and quartz embedded in calcite. It is divided into six microfacies as follow:-

1a) Bioclastic mudstone-packstone

It is generally composed of oyster bearing limestone. The oyster shells are broken, abraded and worn out at places. They, occasionally, show alignment. Ferroan microsparite was developed in some portions of these shells. Such Oyster beds may contian pyrite nodules as in Jaster Gali section. Shells of brachiopodes and unidentified fauna alongwith oyster are composed of nonferroan calcite. The oyster shells are sometimes associated with hard substrate.

1b) Oolitic (bioclastic) Packstone

The oolites are fine to coarse grained, grey in colour, poorly sorted and generally oval to rounded (Plate A-1). Bioclasts, pellets are rare Quartz grains serve as nucleus. The oolites at places are micritized and may superficially appear as pellets. According to shape they are single to compound. Some of the ooids are distorted due to compaction. The calcite is present as matrix and groundmass.

1c) Pelletoidal (bioclastic) Packstone

The pellets are fine to medium grained dark and grey in colour. They are moderately well sorted and generally oval to rounded. Sometimes oblong but somewhat elongated oolites may also occur. They lack nuclei (Plate A-2), however central part of some pellets may be composed of ferroan as well as non ferroan microsparite. They are embedded in non ferroan calcite which at places has been converted to ferroan sparite. Dolomite also substitutes calcite as cement. Bioclast are poorly sorted and abraided.

1d) Arenaceous Mudstone

Carbonate mud is the dominant constituent but the rock contains substantial amount of clastic matter (Plate A-3). The quartz grains are fine to medium grained and subangular to rounded. They are occasionally sutured. They are well to poorly sorted and compositionally mature. The accessories are pellets/oolites, iron oxides, clays, biotite, muscovite, sphene, chert, tourmaline and plagioclase. At places quartz occurs as polycrystalline grains. Bioclasts are unidentified fragments of broken shells. Ferroan calcite occurs as dominant cement. Textural evidence suggests that ferroan calcite was the primary cement. Quartz grains at places occur as clusters, not in contact with one another but rarely showing point contacts.

1e) Arenaceous Dolomite

It contains subrounded to rounded quartz grains which are poorly sorted. However, some polycrystalline grains of quartz also occur. Dolomite (Plate A-4) is secondary in nature. As carbonate is replacing quartz so this unit is interpretted to have been deposited as a sandstone but later on was attacked by carbonate cement.

1f) Marl

This facies occurs as interbeds in sandstone and limestone horizons. It generally varies in thickness from a few centimeters to maximum of 20 cm.

D2) Argillaceous Facies

This facies is constituted of silty as well as clayey shales. They occur as rare beds which vary in thickness from less than a cm to 25 cm. Some thin beds may be carbonaceous.

D3) Arenaceous Facies (Plates A-5, A-6 & A-7)

The arenaceous facies are composed of quartz arenites cemented with quartz/carbonate/clay/glauconite or any combination of these minerals. The microfacies 3a, 3b, 3c and 3d are discussed collectively. These microfacies are composed of fine to medium grained, subangular to subrounded quartz grains. They are poorly to well sorted, texturally and compositionally submature to mature. Subrounded grains are generally in point contacts and others have sutured to concavo-convex contacts. The bimodal lag type deposits contain fine generation of quartz in sutured to long contacts. The quartz grains at places occur as clusters, not in contact with one another but rarely showing point contacts.

Calcite is generally ferroan and replacing non ferroan calcite. Dolomite patches cut ferroan calcite. Carbonate cement at places contains dedolomitized rhombs of ferroan calcite. Carbonate rarely occurs as pellets.

Clay cemented quartz arenite portion contains carbonaceous matter. At places clay occurs as coating around the grains and thin films or aggregate grains or deposited in pores. Muscovite flakes act as reinforcemnt for clay cements. These clays occur as kaolinite or illite and marginally corrodes the quartz grains.

3e) Quartz Wacke

It is fine grained, subangular to subrounded, well sorted and texturally and compositionally mature. The grains are almost of entirely of quartz. A few quartz grains show overgrowths. Most of the clay and haematite has been transported to the site of deposition. The cement (Plate A-8) is predominantly an intimate admixture of clay and haematite with bent and distorted thin books and flakes of muscovite serving as reinforcement. The cement is however unevenly distributed. At places it occurs as patches with quartz grains floating in it. At other places it forms thin films to thin coats around clasts.

3f) Sublithic Quartz Arenite

It contains fragments of the underlying Hazara Formation. This microfacies generally occurs at the base. It is fine to medium grained, subangular to subrounded, moderately to poorly sorted, texturally and compositionally submature. Iron oxides may be the cement at places. Quartz is being replaced by illite/kaolinite. Collophene/dahalite pellets may be present.

Table 4. Facies of microfacies, environment of deposition of Datta Formation at Bara Oater from bottom to top.

Facies	Microfacies	Environment
BXI - Arenaceous Dolomite	**1. Coarse Grained Arenaceous Dolomite with Streaks and Layers of Grit:** It is medium grey with small white specks of quartz. Base slightly irregular with concentration of white grit.	Supratidal/Intertidal
BX - Silty Mudstone	**1. Silty Mudstone**: It is coarse quartz rich silt. It is medium grey with rusty patches. Limonitic specks are present. It is closely jointed.	Lagoon
BIX - Very Fine to Fine Grained Quartz Arenite	**2. Quartz and Carbonate Cemented Quartz Arenite**: It is very fine to fine grained, rounded to subangular, mature and very well sorted. It medium grey to rusty yellow. **1. Carbonate Cemented Quartz Arenite**: It is very fine grained, subrounded to subangular, submature and moderately sorted. Its color is medium grey to rusty yellow.	Middle to Lower Shore Face Middle to Lower Shore Face
BVIII - Arenaceous Limestone	**1. Arenaceous Limestone:** The quartz is very fine grained, subrounded to subangular and well sorted. It is light grey to whitish grey and contains <1mm thick whitish streaks of quartz.	Lower Shore Face
BVII- Fine Grained Quartz Arenite	**1. Quartz and Carbonate Cemented Quartz Arenite:** It is fine grained, subrounded to subangular, well sorted and mature. Its color is light grey to dark grey. It is closely jointed.	Middle Shore Face
BVI- Coarse Grained Quartz Arenite	**1. Carbonate Cemented Quartz Arenite:** It is coarse grained, rounded to subrounded, poorly sorted and submature. It is light grey, slightly glassy looking quartzite with specks of haematite.	Upper Shore Face
BV- Hardground	**Ferruginous Quartz Arenite**: It is medium grained, subrounded, submature and poorly sorted. Its fresh colour is black and weathers to rusty black.	Subareal
BIV- Alternating Bands of Quartz Arenites and Oolitic/Pelletoidal Limestone	**5. Oolitic Limestone**: The limestone is medium to dark grey and weathers to dark grey. **4. Carbonate and Quartz Cemented Quartz Arenite**: It is medium grained, subrounded, poorly sorted and submature. Its color is offwhite to medium grey with limonitic microspecks. **3. Nodular Limestone**: It is dark grey nodular limestone with yellowish dolomitic patches. **2. Carbonate Cemented Quartz Arenite**: It is fine grained, subrounded to angular, poorly sorted and subfracture. **1. Pelletoidal Limestone:** It is light grey limestone and contains brachiopodes.	Shoal Middle Shore Face Intertidal Lower Shore Face Lagoon
BIII- Medium to Fine Grained Quartz Arenite	**2. Clay and Quartz Cemented Quartz Arenite**: It is fine to medium grained, subrounded to subangular, poorly sorted and submature. It is dark grey to rusty grey. **1. Quartz and Clay Cemented Quartzite:** It is fine grained, subrounded to angular, well sorted and mature. It is brownish with some yellowish rusty patches and closely jointed.	Middle Shore Face Lower Shore Face
BII- Fine Grained Glauconitic Quartz Arenite	**1.Glauconitic Quartz Arenite**: It is fine grained, subrounded to angular, well sorted and mature. It is dark grey to greenish grey and shows negative relief.	Subtidal
BI- Medium Grained Quartz arenite	**4. Clay and Quartz Cemented Quartz Arenite**: It is medium grained, subrounded to angular, moderately sorted and mature. It is dark grey, reddish and greenish brown with positive relief. **3. Clay Cemented Quartz Arenite**: It is medium grained, subrounded to subangular, poorly sorted and submature. It is lighter ash grey to lightish greenish grey with yellow patches. Cleavage occurs frequently with negative relief. **2. Clay and Quartz Cemented Quartz Arenite**: It is medium grained, very angular to subrounded, poorly sorted and submature. It is light grey to brownish grey with rusty yellow patches. 1. **Clay Cemented Quartz Arenite:** It is medium grained, subrounded to subangular, poorly sorted and submature. It is ash grey to greenish grey.	Upper Middle Shore Face Upper Middle Shore Face Upper Middle Shore Face Lag deposit.

Table 5. Facies, microfacies and environment of deposition of Datta Formatin at Batangi.

Facies	Microfacies	Environment of Deposition
BtVII - Fine Grained Quartz Arenite	**1. Quartz and Clay Cemented Quartz Arenite:** It is fine to medium grained, subangular and well sorted. Its fresh color is dark grey and weathers to rusty grey to brownish grey. Pyrite nodules are abundant.	Lower Shore Face
BtVI - Pelletoidal/Oolitic Limestone	**1. Pelletoidal/Oolitic Packstone:** Quartz grains are rounded to subrounded. It is medium to dark grey on fresh surface and rusty brown to light grey on weathered surface. Bed are 15 cm to 50 cm thick.	Shoal
BtV - Arenaceous Limestone	**1. Arenaceous Limestone**: Quartz grains are fine to medium grained, subrounded to rounded and moderately to very poorly sorted. This microconglomerate. Bands of grit are abundant. Grit is irregular.	Middle Shore Face
BtIV - Hard Ground	**1. Carbonate and Haematite Cemented Quartz Arenite**: Quartz is fine to medium grained, bimodal, subrounded to rounded and very poorly sorted. Medium grey to dark grey on fresh surface and weathers to rusty brown and dark grey. It contains microconglomerate. Bands of grit are abundant. Grit is irregular.	Subareal/Intertidal/Lag.
BtIII - Very Fine to Fine Grained Quartz Arenite	**1. Quartz and Clay Cemented Quartz Arenite**: It is very fine to fine grained, angular to subangular and well sorted. It is offwhite when freshly broken and weathered color is reddish brown to grey, orange brown and light grey. It is highly jointed. Beds are 12 cm to 35 cm thick.	Lower Shore Face
BtII - Coarse to Medium Grained Quartz Arenite	**4. Quartz Cemented Quartz Arenite**: It is coarse to medium grained, angular to subangular and moderately well sorted. It is offwhite to very light grey on fresh surface and weathers to grey offwhite.	Upper to Middle Shore Face
	3. Quartz, Carbonate and Haematite Cemented Quartz Arenite: Coarse to medium grained, angular to subangular and moderately well sorted quartz arenite. It is very light grey on fresh surface and weathers to offwhitish grey bed are	Middle Shore Face
	2. **Quartz Cemented Quartz Arenite:** Coarse to medium grained, angular to subangular and moderately well sorted quatz arenite. Light grey and weathers to offwhite.	Upper Shore Face
	1. Carbonate Cemented Quartz Arenite: Coarse to medium grained, subrounded and moderately well sorted quartz arenite. Fresh color is brownish red and weathers to dark grey to brown, massive beds are 10 cm to 45 cm thick.	Upper Shore Face
BtI - Hard Ground	**Haematite and Carbonate Cemented Quartz Arenite**: It contains coarse to medium grained, subangular to subrounded, moderately well sorted quartz. It is brownish red on fresh surface and greyish brown when weathered.	Supratidal/subareal

3g) Glauconitic Quartz Arenite

This microfacies (Plate A-9) is very rare. Glauconite occurs as cement and pellets between subrounded to angular quartz grains which are texturally mature.

D4) Hardground Facies

This facies contains haematite/clay/carbonate/quartz as cement (Plate A-10) . This facies is composed of very poorly sorted to moderately well sorted quartz grains. These grains are subangular to subrounded and are fine to coarse grained.

Haematite is generally the cement. However, an intimate admixture of carboante and haematite occur as cement. At places clay may substitute the carbonate. The carbonate is corroding the quartz grains. The quartz grain have plane to concavo-convex contacts.

ENVIRONMENT OF DEPOSITION

The Datta Formation of Hazara area is a transgressive shoreface facies. Continental conditions prevailed prior to the deposition of Datta Formation. The deposition of Datta Formation started with transgression and reworking of the underlying units (mainly Hazara Formation). Since this formation was deposited under changing sea level conditions therefore the predominantly shoreface facies are intercalated with lagoonal mud layers, carbonate shoal, subareal deposits (hard ground) and rarely subtidal deposits. For details of environmental conditions in relatioin to facies and microfacies the reader is referred to Table 2 to 7.

Datta Formation was deposited in two to four cycles, each cycle starting with a hardground (Figure 2). The subareal environment is characterised by ferrugeneous hardgrounds or small coaly layers/pockets. The upper

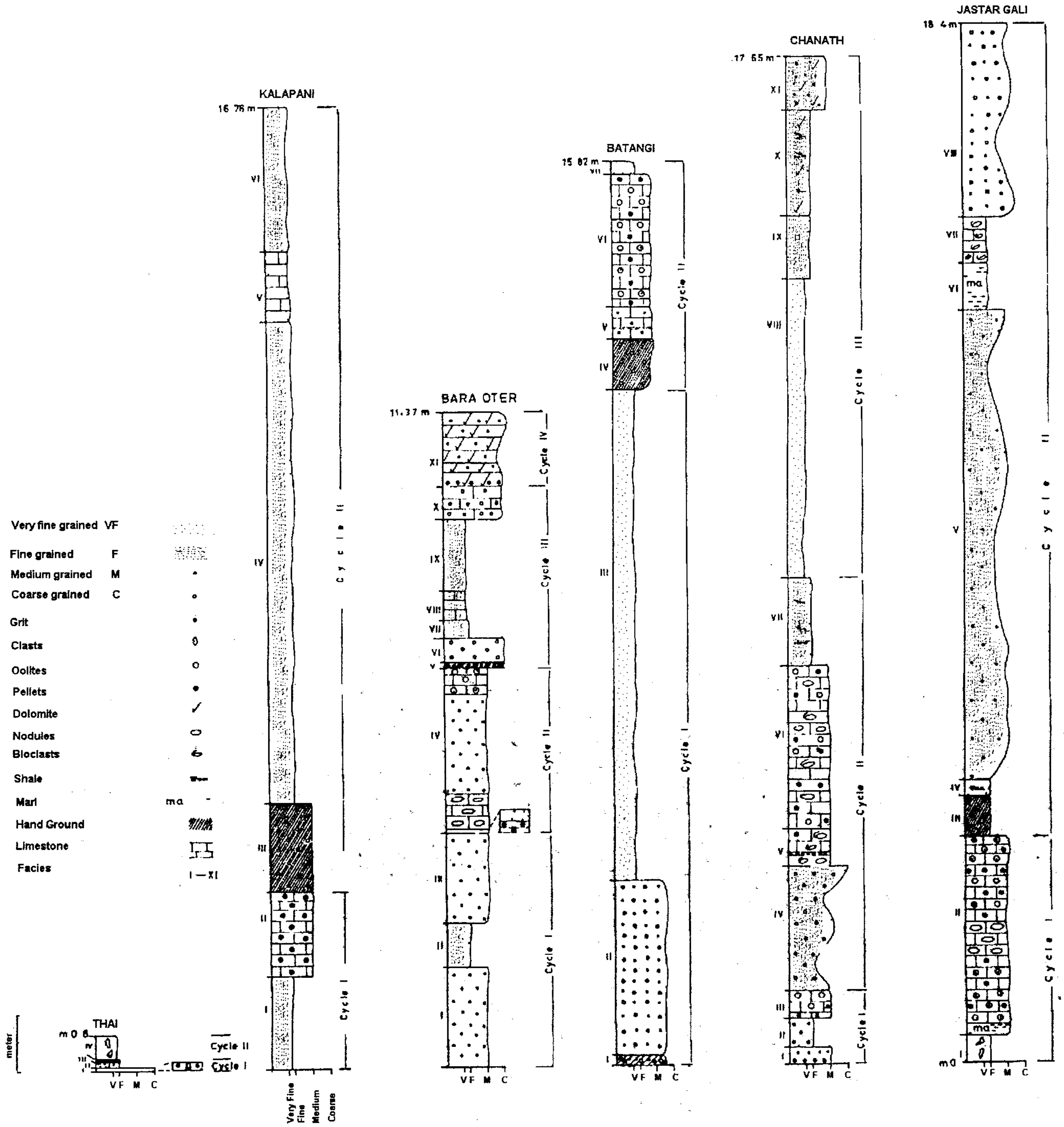

Figure 2- Standardized lithofacies of Datta Formation in Hazara Basin.

shoreface facies is characterised by medium to coarse-grained quartz arenite. While the middle and lower shoreface facies are characterized by medium and fine-grained quartz arenite. Oolitic limestone horizons represent carbonate shoals while marl, carbonaceous shale and pelletoidial limestone represent low energy lagoonal facies.

DIAGENESIS

Diagenesis of Datta Formation in Hazara Basin is discussed as below:

Kaolinite Cement

Kaolinite cement in Datta Formation fills pores. It formed due to the attack of acidic meteoric water on K-feldspar at shallow depths. The early kaolinite cement has now been largely replaced by illite. Only relices of kaolinite still survive. Varying depths for transformation of kaolinite to illite has been proposed by various authors. A burial depth of 3.5 to 4 km for this transformation has been proposed by Bjorlykke and Aagaard (1992); Chuhan et. al, 1992). However detailed studies by Chaudhry et al. (1994) and present work shows that transformation in Datta Formation from kaolinite to illite started between 1000 to 1500 m. Late diagenetic kaolinite cement developed at the expense of surviving K-feldspar. This kaolinite cement is well crystallized and replaces quartz overgrowth over quartz.

Silica Cementation

Quartz occurs as overgrowths around and on the grains. These overgrowths are in optical continuity with quartz grains. The source (Siever, 1972) of silica may be through breakdown and dissolution of silica bearing skeletons of diatoms, radiolarians, siliceous sponges and other silica secreting organisms (Siever et al., 1965; Hurd, 1972). Other source according to Siever (1957) is mineral transformation of silicate.

Carbonate Cementation

In the Datta Formation nonferroan calcite precipitated during early diagenesis under oxidizing conditions (Chuhan et al., 1992) in low energy environment conditions. Such cementation has also been discussed by Todd (1963). Generally carbonate cemented horizons in the Datta Formation occur above the hard grounds. At places ferroan calcite replaces the early kaolinite cement. This may happen in the oxygen deficient realm due to the phase transformatiion of organic matter. This coupled with iron oxides precipitated ferroan calcite or dolomite.

Cement Stratigraphy

The detailed sequence in cement stratigraphy was evaluated from study of the measured sections of the Datta Formation from Kala Pani, Chanath, Jaster Gali, Batangi, Bara Oater and Thai in the Hazara Basin.

It has been observed that early submarine calcite cementation was followed by thin rim early quartz cementation. It was followed by kaolinite, early calcite, dolomitie, ferroan calcite, deep burial quartz and in the last late diagentic kaolinitic cementation phases.

Compaction

Compaction took place through a change in packing by rotation, translation, fracturing and plastic deformation of grains in Datta Formation. The degree of compaction depends upon size, sorting, grain morphology, packing, mineral dissolution, tectonism and grain to grain stresses alongwith loading.

Considering the textural and compositional characteristics and degree of cementation it is estimated that well sorted sands of Datta Formation had initial porosities of upto 40-50%. The porosities are reduced to 25-30% after mild loading which readjusted the grains to a tighter packing (Schmidt and McDonald, 1979). In case of bimodal Datta sands the initial was reduced to 15% or less from original porosity of 30% on loading.

Fractures developed after burial to greater depth and were then filled with carbonate cements.

Pressure Solution

After the cementation of non-ferroan calcite, Datta Formatioin was burried to about 4500m during Miocene resulting in the development of sutured quartz contacts and microstylolites in quartz grains. This accounted for the increase of dissolved silica in pore solutions and stimulating the growth of secondary quartz. The rock was subjected to higher hydrostatic pressures and silica was released to pore fluids resulting in the suturing of grains. Sibley and Blatt (1976) quantitatively determined that pressure solution between the detrital parts of the orthoquartzites could not have supplied more than one-third of the silica present as secondary quartz in the formation.

Dunnington (1967) examined several petroliferous limestones in which stylolites were prominent and inferred from structural considerations that they were formed at depths between 700m and 900m. It can, therefore, be concluded that stylolites in limestone bands were formed earlier than the development of microstylites in quartzarenite.

Late Diagenetic Dolomitization

Isolated patches of dolomite cement are present in many units which are mainly ferroan in nature. The frequent substitution of Mg^{++} for Fe^{++} is a typical late diagenetic feature in Datta Formation. In general the grain size of detrital quartz of Datta Formation embedded in dolomite is much smaller than in the parts not cemented by dolomite thus indicating intensive replacement of quartz by dolomite.

Dedolomitization

The last diagenetic event in Datta Formation is marked by the removal of Mg^{++} ions from ferroan dolomite leading to the formation of ferroan dedolomite. The original rhombic shape of ferroan dolomite is well preserved. This process is accelerated in an environment invaded by fresh waters. During this late stage kaolinite was also emplaced which replaces sutured quartz grains.

Table 6. Facies, microfacies and environment of deposition of Datta Formation at Chanath.

Facies	Microfacies	Environment of Deposition
CXI - Medium Grained Gritty Quartz Arenite with Dolomitic Patches	**Medium Grained Carbonate Cemented Quartz Arenite with Patches of Dolomitic Limestone and Gritty Layers**: Dolomite is present just at the contact with Samana Suk Formation. It is medium grained texturally mature, compositionally submature and poorly sorted. Its fresh color is medium to dark grey and weathers to rusty brown to light rusty grey.	Upper Shore Face/Supratidal
CX - Fine Grained Quartz Arenite with Intercalation of Shale and Dolomite	**Fine Grained Clay Cemented Quartz Arenite and Dolomite Intercalated with Black Shale**: Quartz grains occur as clusters and fine grained. It is mature, angular and well sorted. Clay includes kaolinitoid illite. It is light grey whereas shale is black and 25 cm thick.	Lagoonal/Supratidal
CIX - Fine Grained Quartz Arenite	**Fine Grained Quartz Cemented Quartz Arenite**: It is fine grained, mature, angular to subangular and well sorted quartz arenite. Its fresh color is light grey which weathers to pinkish brown to brownish grey.	Middle Shore Face
CVIII - Very Fine Grained Quartz Arenite	**Very Fine Grained Carbonate and Quartz Cemented Quartz Arenite**: It is very fine grained, mature, well sorted subrounded quartz arenite. It is light grey on fresh surface and weathers to pinkish grey color. Reddish thickness is 30-40 cm.	Lower Shore Face
CVII - Cross bedded Fine Grained Quartz Arenite with Shale	**Fine Grained Carbonate and Quartz Cemented Cross Bedded Quartz Arenite Intercalated with Shale**: It is fine grained, well to poorly sorted, texturally submature and compositionally submature subangular to subrounded quartz arenite. Its color varies from medium to dark grey. It shows rapid alternations with shale.	Minor Channel
CVI - Oolitic/Pelletoidal Nodular Oyster Bearing Arenaceous Limestone	**Fine Grained Nodular and Oyster Bearing Arenaceous Oolitic/Pelletoidal Limestone**: The clastic part is moderately sorted, texturally submature and compositionally mature and subrounded. The carbonate part contains pellets rich in carbonaceous matter. Its fresh color is dark to light grey and weathers to rusty grey.	Barrier
CV - Nodular Limestone/Shale	**Nodular Limestone Intercalated with Shale**: It contains bioclasts and pellets in ferroan calcitic matrix. Its fresh color is dark grey and weathers to light grey. Intercalated shale is dark grey to black.	Lagoon
CIV - Crossbedded Coarse to Fine Grained Quartz Arenite	**Coarse to Fine Quartz and Carbonate Cemented Quartz Arenite**: It is coarse to fine grained, moderately well sorted, texturally mature, compositionally mature and subangular quartz arenite. Its fresh color is light grey to pale white which weathers to pink rusty brown.	Tidal Channel
CIII - Arenaceous oolitic and pelletoidal Limestone	**Medium Grained Arenaceous Limestone**: The sandy portion is medium grained, moderately sorted, texturally submature. Compositionally mature, subangular to subrounded. Oolites and pellets are abundant. Its fresh color is dark grey and weathers to light grey.	Upper Shore Face
CII - Fine Grained Gritty Quartz Arenite	**Fine Grained Carbonate Cemented Quartz Arenite with Streaks and Layers of Grit**: It is fine grained, moderately well sorted, texturally submature, compositionally mature and subrounded quartz arenite. Bedding thickness varies from 8-40 cm. Its fresh color is dark grey and weathers to rusty brown to light grey.	Middle Shore Face
CI - Medium Grained Gritty Sublithic Quartz Arenite	**Medium Grained Carbonate Cemented Sublithic Quartz Arenite with Streaks and Layers of Grit:** It is medium grained, poorly sorted, subangular to subrounded and submature quartz arenite. Few broken collophane/dahllite oolites are present. Its color is dark grey to rusty brown. Microconglomerate range from 2-4mm in thickness.	Subareal to Upper Shore Face

HYDROCARBON POTENTIAL AND POROSITY

The field and petrographic studies show that the Datta Formation is very poor in fossils. The only fauna present is the shells of oysters or plecypodes with minor amounts of unidentified bioclasts. This scarcity of life record indicates that nutrients and living conditions were not favourable. It was due to high energy environment, rapidly changing sea level from subaereal to lower shoreface and input of sand particles. Moreover, few horizons contain organic matter. These horizons are from a few milimeter to tens of centimetres with very low organic production. These were therefore not favourable for substantial hydrocarbon generation (Selley, 1985).

Table 7. Facies, microfacies and environment of Datta Formation from bottom to top at Jaster Gali.

Facies	Microfacies	Environment of Deposition
JVIII - Coarse to Medium Grained Gritty Quartz Arenite	**Carbonate Cemented Quartz Arenite**: The quartz grains are rounded to subrounded, poorly sorted and bimodal. It contains dahllite/collophane oolites. Its color varies from dark grey to brown and rusty brown. It is thick bedded with microconglomerate.	Middle Upper Shore Face
JVII - Limestone	**Wackestone:** It is oyster bearing limestone with pyrite nodules and worm boring. Its fresh color is dark grey and weathers to light grey.	Lagoonal
JVI - Nodular Marl	**Nodular Marl:** It thinly laminated and medium grey to rusty grey marl. It contains nodules which are 1.5 to 4 cm thick and 4-9cm long.	Lagoon
JV - Fine to Medium Grained Quartz Arenite	**Quartz Cemented Quartz Arenite**: It is medium to fine grained, texturally mature, subangular to angular and moderate to well sorted. Its color varies from light grey to reddish brown. Highly jointed bedding is 3-50cm.	Lower to Middle Shore Face
JIV - Fine Grained Quartz Arenite with Intercalation of Shale	**Quartz Cemented Quartz Arenite**: It is fine grained, well sorted, texturally mature well sorted and subangular. Its fresh color is light rusty grey and weathers to rusty brown.	Middle to Upper Shore Face
JIII - Hard Grained	**Quartz and Iron Oxide Cemented Quartz Arenite**: Quartz is fine grained, texturally mature and well sorted fresh color is rusty brown.	Subareal exposure/supratidal
JII - Oolitic Pelletoidal limestone and Nodular Marl	**Arenaceous Oolitic-Pelletoidal Limestone with Marl**: The quartz is rounded. Limestone is grey to medium grey and weathers to rusty brown color. Marl is nodular, 1.5 - 4 cm thick and light grey to rusty brown.	Lagoon
JI - Fine Grained Sublithic Arenite (Lateritized)	**Iron oxide and Quartz Cemented Quartz Arenite**: It is fine grained, subrounded to subangular, submature and poorly sorted. It is massive and gritty. Its color is dark grey to rusty brown.	Upper Shore Face

The Datta sandstones are generally well cemented. The cement is either quartz or carbonates. The hardgrounds are haematite cemented. The porosity is generally low and ranges from 1 to 7% and is enlarged intergranular, oversized fabric selective, intercement and vuggy. However in some areas like Bagh-Seri the porosity may increase in coarse upper shoreface deposits so that the formation is poorly cemented. The Datta Formation for most part overlies Hazara Formation which is comprised of metamorphosed pelites and psemmites. Therefore in most of the Hazara area there is no underlying source of hydrocarbon. At a few places Datta Formation also lies on Cambrian Hazira Formation which is comprised of shales, quartzite, siltstone and is poor in organic matter. In many areas of Hazara, the Datta Formation occurs in the subsurface structures where due to faulting it may be connected directly or indirectly with Chichali, Lockhart, Patala and Margala Hill Formations. In these areas therefore there is a possibility of migration of hydrocarbons into Datta Formation.

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PLATE- A

Figure 1. Oolitic (bioclastic) packstone (1b): (12.5 x 2.5, CNL) Single to compound micritized oolites (a) in sparite (b).

Figure 2.Pelletiodal (bioclastic) packstone (1c): (12.5 x 2.5, CNL). Fine to medium grained pellets in micrite and ferroan microsparite.

Figure 3. Arenaceous mudstone (1d): (12.5 x 10, CNL). Carbonate mud contains substantial amount of quartz (a).

Figure 4. Arenaceous dolomite (1e): (12.5 x 10, CNL). Dolomite(a) occurs as cement and is corroding quartz grains (b).

Figure 5. Coarse grained quartz arenite (3b): (12.5 x 10, CNL). The quartz grains are cemented with calcite Fracture porosity (a).

Figure 6. Medium grained quartz arenite (3d): (12.5 x 2.5, CNL). The quartz grains are cemented with quartz and kaolinite-illite.

Figure 7. Fine grained quartz arenite (3b): (12.5 x 2.5, CNL). In this microfacies carbonate and quartz occur as cements.

Figure 8. Quartz wacke (3e): (12.5 x 2.5, CNL). The cement is composed of kaolinite-illite (a). Quartz (b).

Figure 9. Glauconitic quartz arenite (3g): (12.5 x 2.5, CNL). Glauconite occurs as cement (a) as well as pellets (c).

Figure 10. Hardground Facies (D4): (12.5 x 2.5, CNL). An intimate admixture of clay and haematite is present as cement among the quartz grains.

PLATE A